Theoretical Nuclear Physics Laboratory

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1. Abstract

Nuclei are finite many-particle systems composed of protons and neutrons. They are self-bound in femto-scale (10^{-15}m) by the strong interaction (nuclear force) whose study was pioneered by Hideki Yukawa. Uncommon properties of the nuclear force (repulsive core, spin-isospin dependence, tensor force, etc.) prevent complete microscopic studies of nuclear structure. There exist number of unsolved problems even at present. In addition, radioactive beam facilities reveal novel aspects of unstable nuclei. We are tackling these old problems and new issues in theoretical nuclear physics, developing new models and pursuing large-scale calculations of quantum many-body systems. We are also strongly involved in research on other quantum many-body systems, to resolve mysteries in the quantum physics

2. Major Research Subjects

(1) Nuclear structure and quantum reaction theories

(2) First-principle calculations with the density functional theory for many Fermion systems

(3) Computational nuclear physics

3. Summary of Research Activity

(1) Finite amplitude mothod for nuclear response calculations

We have performed a systematic calculation of nuclear photoabsorption cross section for light nuclei. The calculation is fully self-consistent and is based on the time-dependent density-functional theory with the Skyrme functional. This is achieved using the finite amplitude method we have recently developed. The key feature of the method is to obtain the matrix elements of the random-phase approximation (RPA) in a simple way avoiding explicit calculation of induced residual fields. So far, even-even nuclei up to mass number A=80 have been studied.

In addition, we have been working on extension of the finite amplitude method to nuclei where the pairing correlations are important. The basic equations have been derived and we are currently developing the computer program to calculate the linear response utilizing the finite

amplitude method for the quasi-particle RPA.

(2) Large amplitude dynamics in shape coexistence phenomena

Shape coexistence phenomena in proton-rich Se isotopes have been studied with the adiabatic self-consistent collective coordinate method. The canonical collective variables, mass parameter, and potential were determined self-consistently. The calculation indicates importance of the triaxial degrees of freedom for the tunneling dynamics between two quasi-vacua at prolate and oblate shapes. The collective Hamiltonian was requantized to calculate excitation spectra and transition properties for the first time. The shape mixing is hindered by coupling to the rotational motion to localize collective wave functions around prolate and oblate minima.

(3) Reaction cross section of stable and unstable nuclei

We have studied the difference between the interaction cross section and the total reaction cross section for relativistic energies. We show that, for incident stable nuclei, the predicted difference is large enough to probe the nuclear structure, particularly in a mass region of less than around 40.

We have systematically calculated the total reaction cross sections of oxygen isotopes, $^{15-24}$O, on a ^{12}C target at high energies using the Glauber theory. We have also studied the differential elastic-scattering cross sections of proton-^{20,21,23}O. The agreement between theoretical and experimental results is generally good, and our prediction for proton-^{20}O elastic scattering appears consistent with recent (preliminary) experimental data.

(4) Low-lying collective modes in deformed unstable nuclei

Low-frequency modes of excitation in deformed neutron-rich nuclei have been studied by means of the self-consistent Hartree-Fock-Bogoliubov and the quasiparticle-random-phase approximation based on the Skyrme energy density functional and the pairing density functional. We have investigated soft $K^{\pi}=0^+$ modes in neutron-rich Mg isotopes close to the drip line and have found that its strong collectivity is due to the coherent coupling between the beta vibration and the pairing vibration of neutrons.

(5) Density functional for description of novel pairing properties in nuclei far from stability

Our research focuses on the pairing properties in nucleonic systems under the extreme conditions; super neutron-rich nuclei (N > 2Z) and stellar interiors. We developed an energy

density functional for pairing correlations (pair-DF) toward description of pairing properties in nuclei across the mass table. Our pair-DF is an indispensable ingredient for reliable prediction of the ground states and dynamical properties in super neutron-rich nuclei around heavy and medium-heavy mass regions, which are the main research targets in the RIKEN RIBF. We have completed the extensive calculation from $(N-Z)/A=0$ to 0.4 (neutron drip line region) for all even-even nuclei with $N, Z > 40$. From the analysis, we found the anomalous enhancement of pairing correlations in nuclei with large neutron excess, which can bring about various novel collective phenomena.

(6) Molecular structure of ^{12}Be studied with the generalized two-center cluster model

We have developed the generalized two-center cluster model (GTCM), which can handle the ionic, atomic, and covalent configurations in general two center systems. We have applied the GTCM to a unified study on structures and reactions in ^{12}Be. We have found that, above the alpha decay threshold, various chemical-bonding states coexist with a small energy interval. We also predicted that they were strongly populated through the two-neutron transfer reactions, alpha+^{8}He $->$ ^{6}He+^{6}He, which has been measured very recently at GANIL.

(7) Quantum condensed state of alpha particles in nuclei

We have investigated the quantum condensate state in nuclei, composed of a finite number of alpha particles, which are weakly interacting like a gas and condensed into the lowest mean field 0S orbit. We find a dilute density state in ^{16}O of strong alpha condensate character. The state is located at around the four-alpha breakup threshold as the sixth 0+ state. This discovery in this work is of a great significance in triggering further investigation in heavier nuclei.

(8) Many-body green's function approaches to nuclear structure

Numerical codes for Green's function theory were extended to achieve large-scale calculations using modern realistic nuclear interactions. Ab-initio studies of medium mass nuclei (up to A=60) are now being performed. Calculations for ^{56}Ni have reproduced the known spectroscopic factors. Based on this success, the dependence of nuclear correlations on proton-neutron asymmetry is being investigated. The quenching of experimental spectroscopic factors is currently an open puzzle for drip-line nuclei. Analogous calculations have been performed for electronic systems (atoms) to aid in developments of density functional theory.

(9) Smoothing method of S-matrix elements in CDCC calculations

One of the most reliable methods for treating the breakup processes is the method of continuum discretized coupled channels (CDCC). In CDCC, the calculated S-matrix elements are discrete in

continuum, although the exact ones are continuous. Thus, one needs a smoothing procedure of the S-matrix in order to analyze real breakup processes. For this purpose, we have proposed a simple formula by using the complex scaling method and the validity of the new smoothing method was confirmed by test calculations for three-body breakup reactions. In a future work, we will investigate the practicability of this formula for four-body breakup processes.

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